

Rare D Decays

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We discuss several recent measurements of rare charmed hadron decays. Focus is placed on radiative and annihilation topologies highlighting their sensitivity to new physics and pointing out the strengths and weaknesses of different channels. We compare the different measurement techniques employed at fixed target and e^+e^- dedicated charm experiments, B-factories, and the Tevatron experiments. Comparisons are also made to similar topologies in the beauty, strange, and top systems where appropriate.

I. INTRODUCTION

Many extensions of the standard model (SM) predict anomalous effects in rare decays of beauty, charmed, and strange hadrons that could significantly alter their decay rate with respect to SM expectations. In B meson decays, the experimental sensitivity has reached the SM expected rates for many rare processes. In contrast, GIM suppression [1] in D meson decays is significantly stronger and the SM branching fractions, in the case of radiative D meson decays, are expected to be as low as 10^{-9} [2, 3]. This leaves a large window of opportunity still available to search for new physics in charm decays.

Annihilation topologies of charged mesons can be used to probe new charged current phenomena that would appear at tree level such as models with charged Higgs bosons [4]. Here, the advantage is the SM decay rate can be precisely calculated and the rates are experimentally accessible. Given a priori knowledge of the decay constants and CKM elements, measurements of these processes can place strict bounds on new phenomena.

As a third generation particle, sizable corrections are expected to B^+ annihilation in SUSY models with high $\tan\beta$ [5]. Sensitivity to new physics in these decays are currently limited by statistics but will eventually be limited by errors in V_{ub} and f_B . As a second generation particle, the corrections are expected to be less evident in $D_{(s)}^+$ annihilation [4]. However, statistics are now available to make precision measurements of both $D_s \rightarrow \tau\nu$ and $D_s \rightarrow \mu\nu$. The ratio of these channels can then provide an extremely clean test for models that do not preserve lepton universality.

Radiative meson decay and annihilation of neutral mesons are sensitive to tree level neutral current phenomena or almost any new particle that can interact at higher order through penguin or box diagrams. The SM rate is absent at tree level and thus always suppressed. The precision to which the SM rate can be calculated varies drastically depending on generation and topology. For radiative beauty transitions such as $b \rightarrow s\gamma$ precision measurements and calculations are available [6]. For strange meson transitions such

as $K_L \rightarrow \pi^0\nu\bar{\nu}$, precision calculations exist and the SM rates are expected to be accessible in the next generation of kaon experiments.

For radiative charmed hadron decays such as $c \rightarrow ul^+l^-$, the SM rate is extremely difficult to estimate. However, given the present level of experimental sensitivity, the errors in imperfect cancellation through the GIM mechanism can be ignored and we can essentially treat these decays as forbidden. Thus at the current level of sensitivity, any signal in the charm sector would unambiguously signal new physics. This relation between current experimental sensitivity and SM expectations is also true for annihilation of neutral B and D mesons. In this situation, any improvement of experimental limits allows us to place further constraints on new phenomena.

II. EXPERIMENTAL ENVIRONMENTS

Results are available from a extremely diverse set of experiments. The cleanest environment is e^+e^- at charm threshold such as CLEO-c. Here, beam constraints are a powerful tool in background reduction and CESR has now delivered enough luminosity at particular resonances to allow for competitive studies of rare decays.

Some of the largest charm samples are available at the B-factory experiments Belle and BaBar where the direct charm production cross section is similar to the $\Upsilon(4S)$ production cross section and all species of charmed hadrons are available in the same data set. Since the final state is dominated pions, the excellent particle ID capabilities of these experiments greatly reduces the combinatorial background in D and Λ_c decays where either multiple kaons or protons are present. While not at threshold, the isolation of direct charm production still allows for strong background reduction through global event variables such as the total and missing energy in the event.

Results are available from many fixed target experiments conducted in the last decade at Fermilab with the best limits on rare decays coming from FOCUS [7] that set the bar for the current experiments. The large

boost and excellent vertexing capabilities of these experiments led to large high purity samples of all charm species. While these data sets have now been surpassed by other experiments, they still remind us of opportunities that will become available at LHCb or possibly future dedicated fixed target charm experiments at Fermilab [8] that will have similar analysis strategies but much larger data sets.

Run II of the Fermilab Tevatron has brought the study of rare charm to the energy frontier experiments DØ and CDF. Here again all species are available and the enormous production cross sections more than compensate for the lower luminosity. However for rare decays, the large backgrounds lead to stringent limitations on the channels available for study and to date, only final states containing dimuons have been considered.

III. ANNIHILATION

A. Charged Meson Annihilation

New results are available this summer from the Belle Collaboration on the decay $D_s \rightarrow \mu\nu$ [9]. Belle reports

$$\mathcal{B}(D_s \rightarrow \mu\nu) = (6.44 \pm 0.76 \pm 0.52) \times 10^{-3}.$$

Combining this measurement with PDG'06 [10] and BaBar [11] and CLEO-c [12] measurements from 2007 indicate an experimental sensitivity on the order of 8% in this branching fraction and indicate that the ratio of experimental measurement to theoretical prediction for $D_s \rightarrow \tau\nu/D_s \rightarrow \mu\nu$ can now be determined to roughly 15%. This can be compared to the experiment to theory ratio in $B^+ \rightarrow \tau\nu$ that is measured to a precision of about 44%, the recently observed Belle measurement of $B \rightarrow D^*\tau\nu$ [13] that has a precision of about 30%, or the recent measurement of $t\bar{t}$ production cross section with $t \rightarrow b\tau\nu$ [14] that also has a precision of about 30%. So while the $c \rightarrow \tau$ transition is not expected to have contributions as large as those in the top and b systems, it makes up for it with both experimental and theoretical precision.

B. Neutral Meson Annihilation

The best limits on D^0 annihilation have recently been reported by the CDF [15] and BaBar [16] collaborations. For normalization purposes, both analyses first reconstruct a large sample of D^* tagged $D^0 \rightarrow \pi^+\pi^-$ decays. CDF reconstructs about 1.4k $D^0 \rightarrow \pi^+\pi^-$ decays in a 65 pb^{-1} data sample while BaBar reconstructs greater than 7k $D^0 \rightarrow \pi^+\pi^-$ decays in a 122 fb^{-1} data sample. The CDF analysis focuses on the dimuon final state while BaBar

reconstructs both $\mu^+\mu^-$ and e^+e^- . The possible peaking background from double misidentification of $D^0 \rightarrow \pi^+\pi^-$ as $\mu^+\mu^-$ is studied using large samples of D^* tagged $D^0 \rightarrow K\pi$ decays. CDF sets a 90% CL upper limit of

$$\mathcal{B}(D^0 \rightarrow \mu^+\mu^-) < 2.5 \times 10^{-6},$$

while BaBar sets 90% CL upper limits of

$$\mathcal{B}(D^0 \rightarrow \mu^+\mu^-) < 1.3 \times 10^{-6},$$

$$\mathcal{B}(D^0 \rightarrow e^+e^-) < 1.2 \times 10^{-6}.$$

The final dilepton invariant mass distributions are shown in Fig. 1.

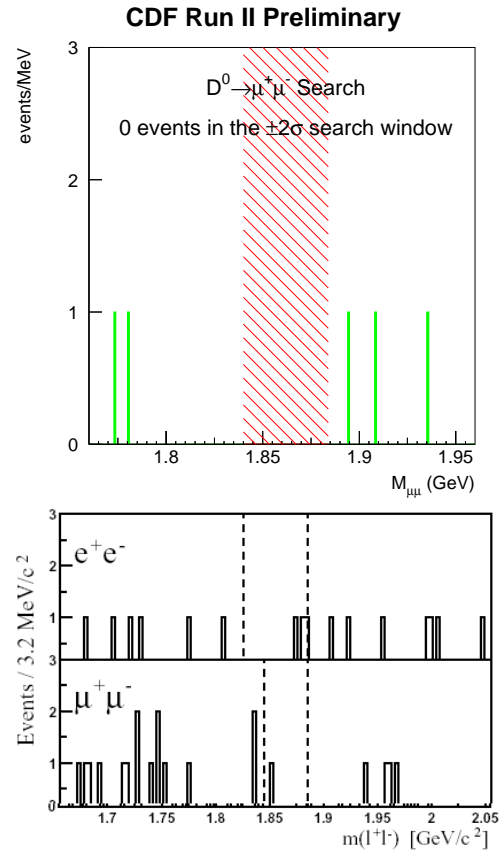


FIG. 1: Dilepton invariant mass distributions from CDF in the dimuon channel (above) and BaBar in the dimuon and dielectron channels in the $D^0 \rightarrow l^+l^-$ analyses.

IV. RADIATIVE DECAY

The first radiative charm decay to be observed is the decay $D_s \rightarrow \phi\gamma$ [17] where Belle measures

$$\mathcal{B}(D_s \rightarrow \phi\gamma) = (2.6^{+0.70}_{-0.61} \rightarrow 0.15_{-0.17}) \times 10^{-5}.$$

This is a beautiful measurement where many of the peaking backgrounds such as $\phi\pi^0$ and $\phi\eta$ could not be constrained using previous information and thus were concurrently measured along with the $\phi\gamma$ final state.

This result is also an excellent example of the inherent problems caused by long distance effects in the charm system. In the above channel, one can not distinguish between the quark level $c\bar{u} \rightarrow s\bar{s}\gamma$ transition and long distance rescattering of intermediate $D^0 \rightarrow \phi\rho$ or $\phi\omega$ transitions into the $\phi\gamma$ final state. Since the rate of these final state interactions can not be calculated with acceptable precision, no limits can be placed on new phenomena using the above channel [18].

This situation can be solved by moving from two-body to three-body radiative decays where the extra kinematic information in the final state allows for a separation of long distance and short distance components [2, 3]. For instance in the decay $D^+ \rightarrow \pi^+\mu^+\mu^-$ the long distance rescattering of $\phi \rightarrow \mu^+\mu^-$ can be extracted from the dimuon invariant mass spectra. Since the short distance component is expected to be three orders of magnitude below the long distance component, any excess in the dimuon mass spectra away from the ϕ resonance would clearly indicate new physics.

The best limits on the $c \rightarrow ul^+l^-$ transition come from CLEO-c [19], BaBar [20], and DØ [21]. The CLEO-c analysis is based on a data sample of 281 pb^{-1} recorded at the $\psi(3770)$ resonance. The excellent calorimetry at CLEO-c leads to a focus on the $\pi^+e^+e^-$ final state. The BaBar analysis is based on 281 fb^{-1} . The combination of powerful hadron and lepton ID systems allow BaBar to search for both dimuon and dielectron final states of D^+ , D_s , and Λ_c . The DØ analysis is based on a 1.3 fb^{-1} data sample. The excellent dimuon trigger system leads to a focus on the dimuon final state. Since the background reduction techniques rely heavily on secondary vertices reconstructed away from the interaction point, focus is placed on the D^+ meson rather than the D_s or Λ_c due to their shorter lifetimes.

As a first step, all three collaborations attempt to establish the long distance component $D^+ \rightarrow \phi\pi^+ \rightarrow l^+l^-\pi^+$ by requiring the dilepton invariant mass be consistent with a ϕ . The results are shown in Fig. 2. CLEO-c finds two events with an expected background of 0.04 events. BaBar sees 19 signal events over a background of about 30 events. DØ sees 115 signal events over a background of roughly 850 events. The differences in the environments are clearly seen in these yield and background comparisons. The three collaborations measure

$$\begin{aligned} \mathcal{B}(D^+ \rightarrow \phi\pi^+ \rightarrow e^+e^-\pi^+) = \\ (2.7_{-1.8}^{+3.6} \pm 0.2) \times 10^{-6} \text{ (CLEO),} \\ (2.7_{-1.8}^{+3.6} \pm 0.2) \times 10^{-6} \text{ (BaBar),} \end{aligned}$$

$$\begin{aligned} \mathcal{B}(D^+ \rightarrow \phi\pi^+ \rightarrow \mu^+\mu^-\pi^+) = \\ (1.8 \pm 0.5 \pm 0.6) \times 10^{-6} \text{ (D/O).} \end{aligned}$$

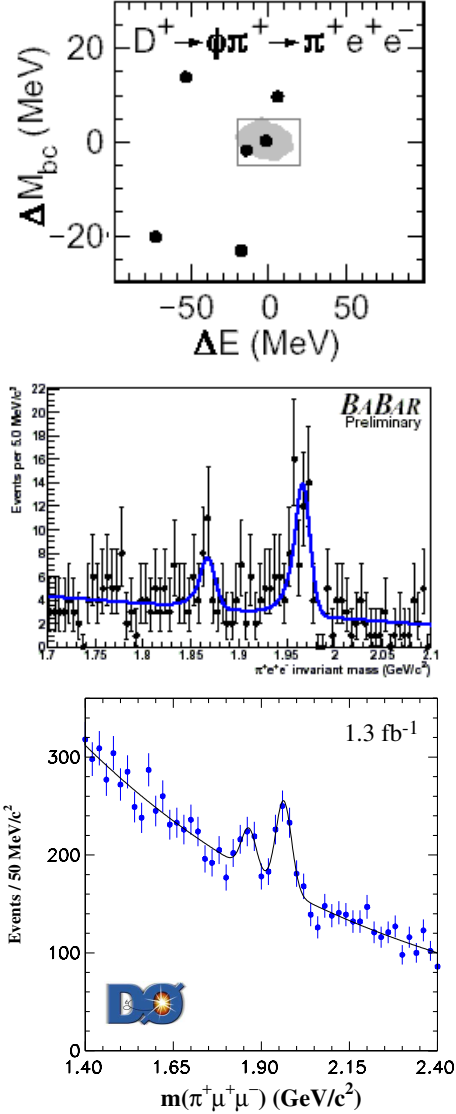


FIG. 2: Results of the search for $D^+ \rightarrow \pi\phi \rightarrow \pi l^+ l^-$. The top figure is the beam constrained mass versus beam energy difference from CLEO in the dielectron channel. The middle figure is the $\pi e^+ e^-$ invariant mass from BaBar. The lower figure is the $\pi \mu^+ \mu^-$ invariant mass distribution from DØ.

With the long distance contribution established, each analysis proceeds to search for the short distance $c \rightarrow ul^+l^-$ transition by looking for an excess of events away from the ϕ resonance. CLEO-c takes advantage of beam constrained variables and detector hermiticity to specifically veto the dominant background of two semileptonic D decays and arrives at a 90% CL upper limit of

$$\mathcal{B}(D^+ \rightarrow \pi^+ e^+ e^-) < 7.4 \times 10^{-6} \text{ (CLEO).}$$

The BaBar analysis requires high momentum D candidates consistent with direct $c\bar{c}$ production to remove backgrounds from semileptonic B decay and then also relies on hermiticity to remove backgrounds from two semileptonic charm decays. Using Λ_c decays easily distinguished using particle ID, they set the best 90% CL upper limit in the dielectron channel of

$$\mathcal{B}(\Lambda_c \rightarrow pe^+e^-) < 3.6 \times 10^{-6} \text{ (BaBar)}.$$

The missing energy resolution of the DØ detector does not allow them to veto semileptonic events where the neutrinos typically carry away a few GeV of energy and the long lived backgrounds from semileptonic charm and b hadron decay are essentially irreducible. However the much more dominant background is from light quark and Drell-Yann production that can be removed using flight length significance, vertex quality, and topological requirements and attempts are made to optimize the analysis for both direct D meson production and D mesons produced in B meson decay. Background reduction based on these variables allow DØ to set the best 90% upper limit in the dimuon channel of

$$\mathcal{B}(D^+ \rightarrow \pi^+e^+e^-) < 3.9 \times 10^{-6} \text{ (D/O)}.$$

The results are shown in Fig. 3. Since many scenarios of new phenomena predict different rates of excess in the dimuon and dielectron channels, its encouraging that together BaBar and DØ can cover both channels.

In conclusion, the last round of results in rare charm decays is producing precision measurements of D_s annihilation branching fractions. The combination of statistical power and results in both the $\tau\nu$ and $\mu\nu$ channel may help add to knowledge recently gained from measurements of $B^+ \rightarrow \tau\nu$, $B \rightarrow D^*\tau\nu$ and $t \rightarrow b\tau\nu$.

The last round of results has also pushed limits on neutral annihilation and radiative decay from the 10^{-5} level to the 10^{-6} level with much of the data currently on tape yet to be analyzed. A complete analysis of the full B factory and Tevatron data sets as well as data at a super B factory and LHCb should push these results to the 10^{-7} level and hopefully yield an anomalous excess.

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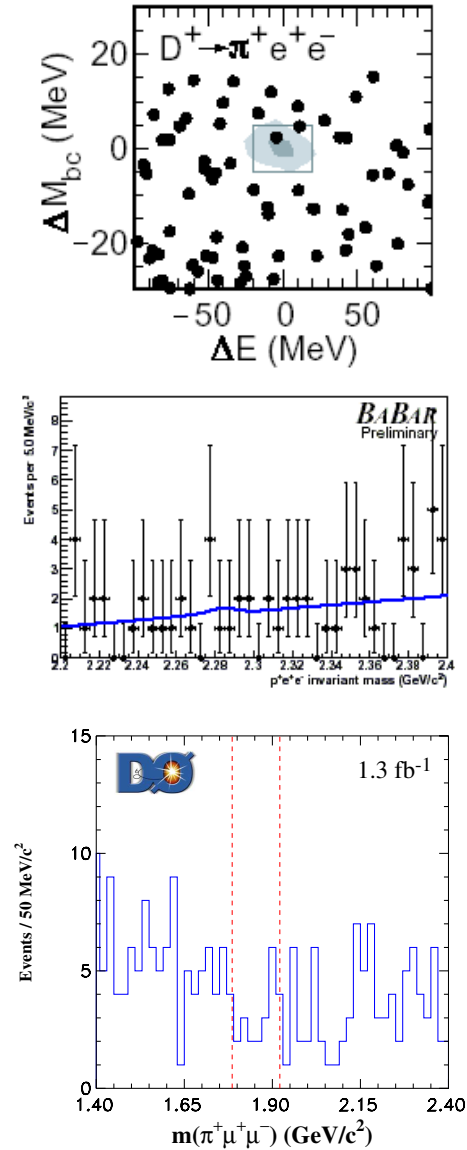


FIG. 3: Results of the search for $c \rightarrow ul^+l^-$. The top figure is the beam constrained mass versus beam energy difference from CLEO in the $D^+ \rightarrow \pi^+e^+e^-$ channel. The middle figure is the $\Lambda_c \rightarrow pe^+e^-$ invariant mass from BaBar. The lower figure is the $D^+ \rightarrow \pi\mu^+\mu^-$ invariant mass distribution from DØ.

per experiment to continue a healthy rare charm decay program.

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